STUDIES FOR STUDENTS

THE PROPERTIES OF BUILDING STONES AND METHODS OF DETERMINING THEIR VALUE[1]

I. NECESSARY CONSIDERATIONS IN THE SELECTION OF STONE

QUARRY observations, building inspection, and laboratory examination of building stone are conducted to satisfy the individual and the public that the stone under consideration possesses a color which will remain permanent and inherent qualities which give it a capacity to effectually withstand the atmospheric and other conditions to which it will be subject when in use.

It is my purpose in this number to discuss: (1) Color; (2) the inherent qualities of stone which limit its capacity to withstand atmospheric and other conditions; and (3) the atmospheric and other conditions to which building stone may be subject. In a following number quarry observations, building inspection, and the laboratory examination of building stone will be considered.

[1] This subject has been discussed very freely by geologists, architects, and engineers for twenty or twenty-five years. Many of the ideas expressed in this and the following number are a repetition of the conclusions reached by men who have previously entered this field of discussion. However, it would be a very uncertain task to endeavor to give any one credit for first enunciating the principles herein stated.

The following is a list of the more important American publications which treat, more or less fully, the subject considered in these studies, and to which the reader is referred: The Experimental Tests of Building Stones, by ROBERT G. HATFIELD, Trans. Am. Soc. of Civil Engineers, Vol. XLVIII, pp. 145–151, 1872; Report on the Building Stones of the United States, Appendix of the Annual Report of the Chief of Engineers, U. S. A., 1875; Notes on Building Stones, by HIRAM A. CUTTING, Vermont, 1880; Building Stones of Colorado, by REGIS CHAUVENET, Report of the Colorado School of Mines, pp. 1–16, 1884; The Building Stones of Minnesota, by N. H. WINCHELL, Report of the Geological and Natural History Survey of Minnesota, Vol. I, pp. 142–203, 1884; Special Report on Petroleum, Coke, and Building Stone, The Tenth Census of the United States, 1884; Report on Building Stones, by JAMES HALL, Thirty-ninth Annual Report of the New York State Museum of Natural History,

Color.—The predominant colors of stone are white, gray, brown, red, yellow, buff, blue, black, and green.[1] Ordinarily the color of a rock is not simple but composite, being a resultant of the different colors of the constituent minerals.

The sedimentary rocks on account of the simplicity of their mineral composition approach more nearly to what is known as a simple color than do the igneous. The shades of brown, buff, yellow, red, gray, or blue imparted by a sedimentary rock are mainly attributable to the presence of the oxide, carbonate, or sulphide of iron, bitumen, and carbonaceous matter in the form of graphite. The white and gray colors of marble, limestone, and dolomite may be attributed to the calcite or dolomite of which the rock may be composed.

pp. 186–224, 1886; The Collection of Building and Ornamental Stones in the United States National Museum, by GEORGE P. MERRILL, Smithsonian Report, Part II, pp. 277–520 1886; Igneous Rocks, by J. F. WILLIAMS, Annual Report of the Arkansas Geological Survey, Vol. II, 1890; Building Stone in the State of New York, by JOHN C. SMOCK, Bulletin of the New York Museum of Natural History, Vol. III, No. 10, 1890; Marbles and Other Limestones, by T. C. HOPKINS, Report of the Arkansas Geological Survey, Vol. IV, 1890; Stones for Building and Decoration, by GEORGE P. MERRILL, John Wiley and Sons, 1891 and 1898; The Onyx Marbles, by GEORGE P. MERRILL, Report of the United States National Museum, pp. 539–585, 1893; Marbles of Georgia, by S. W. MCCALLIE, Bulletin No. 1 of the Geological Survey of Georgia, 1894; Notes upon Testing Building Stones, by T. LYNNWOOD GARRISON, Trans. Am. Soc. of Civil Engineers, Vol. XXXII, pp. 87–98, 1894; The Relative Effect of Frost and the Sulphate of Soda Efflorescence Tests on Building Stones, by LEA McI. LUQUER, Trans. Am. Soc. of Civil Engineers, Vol. XXXIII, pp. 235–256, 1895; Report on Tests of Metals, etc., at Watertown Arsenal; Reports of the United States War Department, pp. 322, 323, 1895; also 1890 and 1894; The Building Materials of Pennsylvania; I, Brownstones, by T. C. HOPKINS, Appendix to the Annual Report of Pennsylvania State College for 1896; The Bedford Oolitic Limestones of Indiana, by T. C. HOPKINS and C. E. SIEBENTHAL, Twenty-first Annual Report of the Department of Geology and Natural Resources of Indiana, pp. 290–427, 1896; Properties and Tests of Building Stones, by H. F. BAIN, Eighth Annual Report of the Iowa Geological Survey, 1898; The Building and Decorative Stones of Maryland, by GEORGE P. MERRILL and EDWARD B. MATHEWS, Report of the Maryland Geological Survey, Vol. II, pp. 47–237, 1898; The Building and Ornamental Stones of Wisconsin, by E. R. BUCKLEY, Wisconsin Geological and Natural History Survey, Bulletin No. IV, 1898. Reference should also be made to the Engineering, Mining, Architectural, Building, Stone, and similar technical journals in which this subject is discussed in current articles.

[1] Speaking from the purely scientific standpoint all of these are not colors, although they are referred to as such in this paper.

When iron occurs in sedimentary rocks, more especially sandstone, it often serves as a cement by which the original particles are bound together. However, it may also occur as an original constituent in the shape of finely disseminated particles. Carbonaceous matter in the form of graphite, or bitumen in the shape of petroleum occurs mainly in limestone and marble, often contributing to these rocks the blue or grayish-blue colors so commonly observed.

Among sedimentary rocks the color varies widely, not only in the same quarry, but often in the same bed. Certain beds in a quarry may have a delightfully cheerful, uniform color, while those immediately above or below may be dull and somber. In many places the coloring matter is distributed through the beds in regular bands, but occasionally it is very curiously disseminated, forming irregular, fantastic figures. White sandstone is often colored with large and small brown spots, while brown sandstone is sometimes similarly variegated with white spots. All stone which is distinctly mottled or irregularly colored is known as "variegated stone."

The color of an igneous rock is usually composite, as a result of the blending of the distinct colors of the mineral particles. The color, however, does not depend entirely upon the colors of the individual minerals, but in part upon the size and distribution of the constituent particles. In some instances the individual grains are sufficiently large to retain their own color, and the stone is spoken of as being mottled.

With respect to color, granites are ordinarily classified as red and gray. Whether a granite belongs to the first or second class will depend mainly upon the red or white color of the feldspar. Many granites contain both red and white feldspar, but as long as the red variety is sufficiently abundant to impart a reddish tone to the rock, it is called red granite. The most brilliant red granites have a preponderance of medium-sized, deep red feldspar individuals. As the feldspar individuals become finer grained and less deeply colored and biotite, amphibole, or pyroxene becomes more abundant, the color is subdued producing dull red effects.

The gray granites are dark or light colored, depending upon the size of the individual grains and the amount and kind of the ferro-magnesian minerals present. The light-colored granites have a preponderance of white feldspar and quartz, with muscovite as the main ferro-magnesian mineral. The dark gray granites contain less feldspar and quartz, and a greater abundance of biotite, hornblende, pyroxene.

Other igneous rocks such as "labradorite granite" with its blue iridescent color, and rhyolite with its almost black color, are commonly met with. The iridescent color of the former is imparted by the abundant porphyritic individuals of labradorite, of which the rock is largely composed. The black color of the latter is due largely to its semi-crystalline groundmass, which often abounds in fine crystals of hornblende. Serpentine is an abundant constituent of some rocks, and as such imparts to them a green color. The dull greenish-gray color so conspicuous among the basic rocks such as gabbro, diorite, and diabase, is imparted mainly by the minerals of the hornblende, pyroxene, amphibole, chlorite, and epidote groups.

The color of a rock when freshly quarried may be almost perfectly white but a few years, or perhaps months, of exposure to the weather may change the color to a buff, or streak it with irregular patches of brown. Such color changes result chiefly from the presence of easily decomposed minerals within the stone itself. The yellow color of many limestones is due to the presence of finely disseminated iron, as the carbonate or sulphide, which has altered to the oxide. If a stone contains either of these the color will change as a natural consequence of exposure to the atmosphere. The oxides of iron are more stable compounds than the sulphide or carbonate, and very seldom cause a change in color.

A change in the color of the stone in a wall may be due to impurities in the mortar, cement, brick, or water used in the construction and not to the presence of easily decomposed minerals in the stone. The committee appointed to investigate the cause of the brown stains on the walls of the State Historical Library

Building at Madison, Wis., reported that the Bedford limestone, out of which the building is constructed, was practically free from ferrous iron, and that the cause of the iron staining was attributable mainly to the cement used in the back wall. This is probably a frequent cause of discoloration, on account of which good stone has been condemned. A common method of preventing the ferrous iron in the brick or mortar of the back wall from coming to the surface, is to use a coat of asphalt between this and the stone facing. A better precaution would be to select lime, cement, and brick from which ferrous lime is known to be absent.

A change of color through the decomposition of iron sulphide and carbonate is manifest mainly among the light colored rocks. The blue or gray limestones and dolomites are often discolored by spots or irregular efflorescent patches of calcium or magnesium sulphate, which appear as a white precipitate on the surface. Their presence at this place is attributed to interstitial water, which comes to the surface bearing soluble salts of magnesium and calcium, mainly the former. Dark colored rocks such as brown sandstone do not discolor, but occasionally they take on a lighter tint after long exposure to the weather. This comes about through the loss of iron oxide which is washed off from the surface by the rains. Decoloration, however, takes place so slowly that it is not an important consideration.

Very often, through long exposure in the quarry a rock, such as the blue limestone of the Trenton formation, is partly or entirely altered in color to a buff. Near the surface, beds may be found that have been completely altered, while deeper in the quarry one passes from those that are partly altered to those that are unchanged. The alteration commences along the joints and gradually passes toward the center of the blocks.

The manner in which a stone is dressed sometimes affects the permanency of its color. A rough dressed stone furnishes a multitude of places in which dust and dirt may lodge, while one which is smooth dressed is free from such places. For this reason there is less danger of the original color being obscured in a smooth

than in a rough dressed stone. On the other hand a smooth dressed stone emphasizes blemishes in color which may be obscured by rough dressing. These color blemishes may be more unsightly than the "tan" of smut and dust, in which case it would be preferable to rough dress the stone.

Fashion, dominated by color, influences the exploitation and the market value of different stones. Until a few years ago brownstone was preferred, both for business blocks and residences, but people became weary of gazing at long rows of somber colored buildings and the fashion changed to light colored stone. At the present time immense quantities of light colored stone are being used, but the fashion will change again in a few years and the pendulum will swing back to brownstone. A judicious use of both would serve to relieve the monotony of long rows of brownstone buildings and of the dazzling glare of white limestone and marble. It is to be hoped that the time will come when the use of neither light nor dark stone will be supreme.

In the large cities, other things being equal, the permanence of color ought to be a factor worthy of consideration in the erection of residences and tenement houses. However, in the construction of business blocks it scarcely warrants serious attention. A white limestone or marble structure erected in the midst of a business portion of a large city soon loses its original color, becoming gray and dingy from the omnipresent smoke and dirt. If the limestone is bituminous and contains a small amount of oil, all the dust and smoke which chances to fall upon it will be retained. The walls of most of the buildings in the business section of our large cities eventually become so begrimed with smoke and dust that it is barely possible to tell whether the stone was originally dark or light colored. One needs to familiarize himself with the characteristic brown and gray shades of stone which have been steeped for years in a smoke and dust laden atmosphere, in order to be able to determine the original colors.

On the whole the dark colored stone shows much less than does the light the effects of smoke and dust. Nevertheless the

only consideration in the selection of stone to be used in the business portion of a large city should be strength and durability.

In the suburban and resident parts of a city and in rural districts, where smoke and dust are trifling matters, the original color will not suffer seriously from external causes alone. In these places beauty is one of the chief ends of architecture, and a judicious scattering of light and dark colored stone buildings adds very materially not only to the appearance of the street as a whole, but also to the beauty of the dwellings individually.

When used for interior decorations, a stone does not suffer materially from atmospheric agencies, and the color will ordinarily remain permanent. The selection of stone for these uses, then, becomes largely a question of taste. A color which harmonizes with the surroundings or matches the other work, is generally considered most appropriate. In the flooring or steps, the capacity which the stone has to withstand abrasion without becoming unduly slippery, and not color, should be the controlling factor.

For monumental purposes the taste of the purchaser is again the main, controlling factor in the color selected. The stones used for monuments are mainly igneous and metamorphic (granite and marble), and as such contain few minerals which will result in discoloration. If pyrite or marcasite are constituents of the stone there will be danger of discoloration. However, the fact that most of the water which falls upon a granite monument is shed by its polished surface, lessens the danger of discoloration, by preventing decomposition.

In the more common uses to which stone is put, such as road making, sidewalks, retaining walls, cribs, breakwaters, bridge abutments, etc., the element of color seldom enters. In the case of retaining walls and sidewalks, which are partially ornamental in nature, color should receive appropriate consideration.

II. INHERENT QUALITIES OF STONE

The capacity which a stone has to withstand the forces tending to destroy it, is known as durability, and depends upon the

mineralogical composition, and the texture or state of aggregation of the mineral constituents. A consideration of the mineralogical composition implies reference to the characteristics of the different kinds of minerals and their relative abundance. By texture is meant the size, shape, manner of contact, and arrangement of the mineral particles. The strength, hardness, elasticity, structures, the effect of alternating heat and cold, and the effect of acids, depend upon both the mineralogical composition and the texture. The specific gravity as ordinarily computed depends upon the mineralogical composition alone; the porosity on the texture; and the weight per cubic foot on the specific gravity, and porosity.[1]

Mineralogical composition.—The most common minerals that enter into the composition of building stones are quartz, feldspar, mica, calcite, dolomite, kaolin, pyroxene, amphibole, and serpentine. These minerals have a respective hardness of 7, 6, 2–3, 3, 3.5–4, 1, 5–6, 5–6, 3–4. With the exception of quartz they all have one or more well-developed cleavages.

Quartz is perhaps the commonest of these minerals. It is the hardest, but probably neither the strongest nor most elastic.[2] Under ordinary conditions of temperature and pressure it is little, if at all, acted upon by the common acids. These conditions, combined with the fact that it possesses no ready cleavage, makes it one of the most durable and stable rock-forming minerals.

Feldspar is also a very common mineral, especially in the igneous rocks. It is softer than quartz, but probably stronger and more elastic. It cleaves readily in two directions. Under ordinary conditions of temperature and pressure it is little acted upon by the common acids. In the quarry, decomposition of

[1] It has been customary to consider the minerals of igneous rocks as primary, and secondary, while the secondary mineral matter in sedimentary rocks is known as cement. In this paper minerals are considered without reference to their origin, and therefore the terms secondary, primary, and cement, have been purposely omitted.

[2] Thus far I have been unable to obtain the crushing strength or coefficient of elasticity of the common minerals. I expect that these constants have been determined although my attempts to obtain them have been unsuccessful.

feldspar takes place very slowly, but owing to the fact that it often occurs in granite and other rock of great age, it is frequently in an advanced stage of alteration. The alteration products of feldspar are objectionable only in so far as they yield more readily to disintegration.

Mica is also a very common mineral, occurring most abundantly in the metamorphic rocks. The ready cleavage by which the mineral splits into thin plates, provides an easy passage for water, by which disintegration proceeds more rapidly than in the associated minerals. Mica is undesirable in proportion to the size of the individuals. If present in small isolated flakes, as it ordinarily occurs in sandstone, it is scarcely less durable than quartz and feldspar, but if the individuals are large or the flakes clustered together, disintegration will proceed more rapidly. Decomposition through chemical agencies goes on very slowly.

Calcite is almost as common as quartz, although far less permanent at the surface of the earth. It possesses three prominent cleavage directions, on account of which it disintegrates quite readily. The hardness, and probably the strength and elasticity, are all less than in quartz. It is quite easily soluble in carbonated waters and is readily acted upon by cold, dilute hydrochloric acid.

Dolomite differs from calcite mainly in its somewhat greater hardness, and the greater difficulty with which it dissolves in cold dilute hydrochloric acid. Its cleavage, hardness, strength, and elasticity are such that it disintegrates almost as readily as calcite, although it is taken into solution somewhat more slowly.

Kaolin is an important constituent of slate, being however, mainly of secondary origin. It is one of the softer minerals, has a perfect cleavage, and readily disintegrates. It is not acted upon chemically except under the most favorable conditions.

Pyroxene is one of the less important building-stone minerals. It cleaves perfectly in two directions, and breaks down slowly through mechanical abrasion. It gradually decomposes in the quarry when in the presence of water.

Amphibole has about the same strength and capacity to withstand abrasion and chemical influences as pyroxene.

Serpentine occurs in certain green colored rocks, such as verde antique, and is usually an alteration product of olivine.

Among the accessory mineral substances in building stones may be mentioned *pyrite*, *marcasite*, *hematite*, *magnetite*, *graphite*, *and bitumen.* Pyrite and marcasite in which the iron occurs partly in the ferrous state decompose quite rèadily in the presence of moisture, forming ferrous sulphate, which is brought to the surface by capillarity and deposited as iron oxide. Through the decomposition of pyrite, occurring in limestone or dolomite, magnesium and calcium sulphates are formed, which are taken into solution and redeposited at the surface as a white efflorescence.

Hematite and magnetite frequently impart a red, brown, yellow, or black color to the stone, but are not considered harmful.

Carbonaceous matter occurs in the form of graphite, and bituminous matter in the form of petroleum. The gray and black shades of limestone and marble are often due to the abundance of graphite. Petroleum occurs mainly in limestone, and is objectionable on account of the discoloration which is apt to result from the adherence of dust.

The occurrence of gaseous inclusions in the minerals, especially in quartz, is said to be a cause for the shattering of a rock when subjected to high temperatures. To what extent these inclusions influence the results of high temperatures on rock is unknown. The probability is that any temperature which would make these gases active agents of destruction would destroy the rock through unequal expansion of the mineral particles.

The hardness, strength, elasticity, and resistance of the stone to chemical action and alternating temperatures is influenced by the relative abundance of the mineral particles. If the percentage of quartz is large, the hardness is proportionately great—provided the size, shape, arrangement, etc., are constant. The strength and elasticity also increase as the minerals in which these properties are best developed are increased. However, it must be understood that a mineral which is high in the scale

of hardness may have a comparatively low crushing strength and elasticity. Any increase in the percentage of this material will increase the hardness of the rock at the expense of strength and elasticity. Of course, the elasticity, hardness, and strength are not controlled by the one factor of abundance. A rock may consist entirely of the strongest minerals, and yet the size, manner of contact, and arrangement may be such that it will be one of the weakest.

TEXTURE OR STATE OF AGGREGATION

As outlined above the texture of a rock has reference to the size, shape, manner of contact, and arrangement of the mineral particles. The size of the particles affect the weathering of a stone by increasing the differential disintegration. When the mineral particles are large they disintegrate and weather out most easily, often leaving small depressions, on account of which the surface has a pitted appearance. The larger mineral particles have more pronounced cleavage cracks which increase the rate of weathering. Chemical agents have a better chance to operate and the stone is weakened throughout. Rocks which are composed of small mineral particles may have correspondingly small pore spaces, although the size of the pores is largely controlled by the shape and manner of contact of the grains.

The shape and manner of contact of the grains influence the strength and durability of the stone, as much perhaps as any of its other qualities. If the grains are close fitting the adhesion will be increased and the pore space decreased. When the grains are irregular in outline they usually interlock after the manner of dovetail work, which adds to the strength and lessens the pore space.

Upon the arrangement of the grains depends the laminated schistose, or cleavage structure in rocks. If the mica or other minerals are arranged with their longest axes in a common direction and concentrated along certain planes the rock will possess a capacity to part most readily in that direction and along those planes. The perfection of development of the parting capacity will be influenced also by the size of the grains.

The size, shape, manner of contact, and arrangement of the grains control the size of the pores and the percentage of pore space.[1] The porosity of a rock is an important factor, influencing the danger from alternate freezing and thawing of included water.

The pores, or spaces between the grains, which are connected in such a manner as to allow water to flow from one part to another have been divided for convenience into three classes.

The first class consists of small interspaces that exist between the grains of a rock, known as pore spaces; the second class consists of those openings which form along bedding, jointing, and fissile planes, known as sheet openings; the third class are those openings caused by the removal of several or many of the individual grains, commonly known as cavities, caves, or caverns. All of these openings frequently occur in the same rock.

Pores are ordinarily conceived of as being connected so as to form irregular-shaped tubes. Naturally they differ very greatly in size, depending upon the fineness and shape of the original particles composing the rock and the extent to which the interstices have been filled with secondary mineral matter. In the same rock all the pores are never of the same size, although they may have a general correspondence in size. The pores spaces are classified according to size into capillary and subcapillary. The capillary pores are the larger and the water which they hold is known as the water of saturation. Openings included in this class are over .00002 centimeter in diameter[2] If a rock containing capillary pores is allowed to drain off naturally, a portion of the water will escape, but another portion will

[1] It has been pointed out in another place that pore space in sedimentary rocks depends largely upon the size and shape of the grains and the amount of cement. In general this is true, but the cement itself becomes an individual grain, when once deposited in the interspace of a rock, and the shape and size of the cement grains should be considered. All particles of which a rock is composed should receive consideration as constituent grains of the rock.

[2] Metamorphism of Rocks and Rock Flowage, C. R. VAN HISE, Bulletin of the Geological Society of America, Vol. IX, p. 272.

remain which is known as the water of imbibition. The subcapillary pores are conceived to be of such a size, smaller than .00002 centimeter in diameter, as to contain only the water of imbibition.[1]

As in the case of pores, Professor Van Hise has classified sheet openings which occur along bedding, jointing, or other fissile planes, as capillary and subcapillary, including in the latter all such as are less than .00001 centimeter in thickness.[2]

The third class of openings consisting of cavities, caves, and caverns are a result of the removal of one or more of the grains of which a rock may have been originally composed. They occur most commonly in limestone or dolomite, although present in other less readily soluble rocks.

III. EXTERNAL CAUSES OF DECAY

In the selection of a stone for any purpose a consideration of the climatic conditions under which it is to be placed, is of very great importance. A uniform climate in which the temperature is always above the freezing point is most favorable to long life. A dry climate is conducive to stability, while a moist or humid atmosphere promotes decay. A stone which will withstand the vicissitudes of a moist, temperate climate, where there are long seasons of alternate freezing and thawing, short hot summers, and cold winters, must be of the most enduring kind. The well preserved condition of the monuments of Rome and other cities of the Mediterranean basin, after centuries of exposure, is not due so much to the inherent qualities of the stone, as to the warm, dry atmosphere. The obelisk of Luxor stood for centuries in Egypt without being perceptibly affected by the climate, but after only forty years of exposure in Paris it is now filled with small cracks, and blanched.[3] The same is true of the obelisk in Central Park, New York, from which many pounds of small fragments have fallen.[4]

[1] *Ibid.* [2] *Ibid.*

[3] A. A. JULIEN: Tenth Census, Vol. V, p. 370.

[4] J. C. SMOCK: Bulletin N. Y. Museum, Vol. II, No. 10, p. 385.

The external forces of destruction may be conveniently considered in two classes: (1) those that produce changes through mechanical disintegration and (2) those that produce changes through chemical decomposition. In the case of disintegration the adhesion between the particles or the cohesion of the particles themselves is overcome, and the rock ultimately crumbles into sand or powder. In the case of chemical changes the identity of the mineral particles themselves is destroyed, by the minerals being broken up into other compounds.

The following is a general classification of the agents of mechanical disintegration and chemical decomposition:

I. AGENTS OF MECHANICAL DISINTEGRATION

A. Temperature Changes.
   1. *Unequal expansion and contraction of the rock and its mineral constituents.*
   2. *Expansion occasioned by the alternate freezing and thawing of the interstitial water.*

B. Mechanical Abrasion.
   1. *Water.*
   2. *Wind.*
   3. *Feet.*

C. Growing Organisms.

D. Careless Methods of Working and Handling Stone.

II. AGENTS OF CHEMICAL DECOMPOSITION.

A. Water-solvent Action.

B. Carbon Dioxide.

C. Sulphurous Acids.

D. Organic Acids.

Temperature changes.—Injuries to a stone through changes in temperature are occasioned in two ways: (1) By the unequal expansion and contraction of the rock and its mineral constituents, and (2) through expansion due to the alternate freezing and thawing of the interstitial water.

Unequal expansion and contraction of the rock.—The heat conductivity of stone is very low. A stone a few inches in thickness may be heated on one side to a temperature sufficiently high that it will not bear handling, while on the other side the stone may be comparatively cold. The actual expansion of different kinds of stone has been experimentally determined by W. H. Bartlett,[1] in which he obtained the following results:

Granite,	.000004825 inch per foot for each degree F.
Marble,	.000005668 inch per foot for each degree F.
Sandstone,	.000009532 inch per foot for each degree F.

The diurnal changes in temperature in this latitude are often as much as 50° F., while the annual variation in temperature exceeds 150° F. A difference of 150° F. would make a difference of one inch in a sheet of granite 100 feet in diameter.

Each mineral of which a stone is composed has a different rate of expansion. Whenever a stone is heated each particle presses against its neighbors with almost irresistible force. When cooling begins, contraction sets in which initiates stresses pulling the individuals apart. The inequalities in the rate of expansion of the different mineral particles initiate stresses in rocks having a heterogeneous composition, which tend to separate the individual minerals from their neighbors. The result of these alternating temperatures is to weaken the rock and produce small cracks into which water may percolate or roots descend.

Besides the unequal expansion and contraction of the mineral particles, there is an unequal expansion and contraction between the different laminae or hypothetical layers of the rock which are near enough to the surface to be affected by the atmospheric temperatures. The layer at the surface suffers the greatest change in temperature, and is therefore most affected. Each succeding layer is less affected until a point is reached where there is little or no change in the temperature the year around. Owing to the rapid diurnal changes in temperature in some regions forces are constantly at work tending to separate the superficial stratum from those immediately below.

[1] American Journal of Science, Vol. XXII, 1832, p. 136.

The igneous rocks on account of their heterogeneous mineralogical composition, interlocking character of the mineral individuals, and difference in size, are more liable to injury from the diurnal changes of temperature than are the unaltered sedimentaries.

Investigation shows that, in arid regions, very great work is accomplished simply through expansion and contraction due to diurnal temperature changes. Merrill, in his "Rock Weathering," cites an instance in Montana where he found "along the slopes and valley bottoms numerous fresh, concave, and convex chips of andesitic rock, which were so abundant and widespread as to be accounted for only by the diurnal temperature variations. During the day the rocks became so highly heated as to become uncomfortable to the touch, while at night the temperature fell nearly to the freezing point."[1] Livingstone reports the temperature of rock surfaces in Africa to rise as high as 137° F. in the day, and cool off so rapidly by night as to split off rocks weighing as much as 200 pounds. The expansive force of heat is well shown in many of the limestone quarries in Wisconsin, where beds from five to six inches in thickness are for the first time exposed to the heat of a summer's sun. These thin beds become heated throughout their entire thickness and arch up on the floor of the quarry, generally breaking and completely destroying the stone.

Many buildings show the effect of weathering on the side exposed to the direct rays of the sun, while the sheltered side remains uninjured. The only rational explanation for this is found in the diurnal temperature changes. Ordinarily the movements due to temperature changes are necessarily small, but after centuries of time they must invariably result in the weakening and final disintegration of the stone.

Expansion occasioned by the alternate freezing and thawing of the included water.—The effects of diurnal temperature changes as described above, are small when compared with the action of continued freezing and thawing on a rock saturated with water.

[1] GEORGE P. MERRILL: Rocks, Rock Weathering, and Soils, p. 181.

The expansive force of freezing water is graphically described by Geikie "as being equal to the weight of a column of ice a mile high, or little less than 150 tons to the square foot." One centimeter of water at 0° C. occupies 1.0908^{cm} in the form of ice at 0° C. It is this expansion of about one tenth that does the damage when confined water solidifies.

Water finds its way into the rocks through openings or hollow spaces which are everywhere present. Where the pores are large the stone contains water of saturation which is given off with comparative readiness, but the nearer the pores or sheet cavities approach those of subcapillary size, the greater is the tenacity with which the water is retained. One can readily understand how the particles composing a rock may be so closely fitted together, that the pores will be mainly of subcapillary size. Such a rock will contain only the water of imbibition which will be given off very slowly, on account of which the attendant dangers from freezing will be increasingly great. In general it may be said that the danger from freezing will be increasingly great as the pores approach in size those of subcapillary dimensions.

Two rocks, one of which has very minute interstices and the other of which has large pores may have a capacity to absorb equal amounts of water. The former, however, will be in much greater danger from alternate freezing and thawing. Of two equally saturated rocks, one with 10 per cent. and the other with 3 per cent. of pore space, in which the pores are of equal size, the more porous one will be in greater danger of freezing. The percentage of the pore space that is filled with water will also condition the results of freezing. If two thirds of a rock is saturated greater injury will result from its freezing than if only one third were saturated. If none of the pores are more than nine tenths filled with water, the effect of freezing will be nothing, because the increased bulk of the frozen water will no more than fill the spaces between the grains.

The amount of water contained in the pores at a given time depends, of course, upon the amount of water initially absorbed,

the time that has elapsed since absorption, the condition of the atmosphere, the size of the pores, and the position of the stone. It is only in exceptional cases that the stone in the wall of a building is saturated. However, if the pores are of greater than subcapillary size the water of saturation will, as a rule, be quickly removed, except in the lower courses below the water line.

It would, therefore, appear that the most important factor in estimating the danger from freezing and thawing, is the size of the pore spaces, which controls the rate at which the interstitial water is given up. The second factor of importance is the amount of water contained in each of the pores at the time of freezing. The third and last in importance is the total amount of pore space.

T. S. Hunt, in "Chemical and Geological Essays," says: "Other things being equal, it may properly be said that the value of a stone for building purposes is inversely as its porosity or absorbing power." This statement has been quoted by various authorities, one of whom says: "Other things being equal, the more porous the stone the greater the danger from frost." The mistake has often been made of estimating the danger from freezing by the capacity which a stone has to absorb water. Likewise the capacities which two stones have to withstand weathering are constantly being compared from the standpoint of the ratios of absorption. Such estimates and comparisons are very misleading, for one should not only know the capacity which a stone has to absorb water, but he should, above all, know and consider the relative size of the pores.

The injurious effects of the freezing of the "quarry water," as the interstitial water is called by quarrymen, has long since been known to contractors, who generally refuse to accept stone, especially sandstone, which has been exposed to the action of freezing before being seasoned. Where it is possible, quarrymen sometimes flood their quarry during the winter months, in order to protect the stone immediately at the surface.

The openings formed along bedding, jointing and other fissile planes, permit a freer circulation of water than the pores in the

rock. After an abundant fall of rain or when the snow melts in the spring, the cracks, crevices and pores in the rocks cannot carry away the water nearly as rapidly as it collects in these passages at or near the surface. If the temperature at such a time is fluctuating between freezing and thawing, the water will be alternating in a liquid and solid state. As the water congeals again and again the walls are pressed farther and farther apart. The ice acts as a wedge which automatically adjusts itself to the size of the crack, until the opening is sufficiently wide and deep to allow the free passage of the water. Not only are the cracks and crevices very much enlarged and extended through the stresses exerted by the solidification of the water but the stone is in itself materially weakened.

The danger from the freezing of water collected along parting planes must not be confused with the danger attendant upon the freezing of water which fills the pores of the rock. The compact, thoroughly homogenous rocks, without bedding or other parting planes, whether sedimentary or igneous, are in less danger from alternate freezing and thawing than those in which these structures occur.

Alternate freezing and thawing of the included water has been one of the most potent causes for the decay of building stone, more especially that stone which is bedded or otherwise laminated. The most disastrous results occasionally occur from using stone which has not been properly seasoned, and in cases where the stone has been laid on edge instead of on the bed. In the first case the stone is materially weakened throughout by freezing, while in the latter exfoliation or scaling is liable to ensue. The most trying place in a building, in which to place a stone, is at the "water line," where saturation is most common and the greatest alternations of freezing and thawing occur. The conditions are more severe in the case of bridge abutments and retaining walls than elsewhere. In bridge abutments the courses of stone at the level of the water are often badly shelled and broken, while the stone above and below is scarcely injured. It is not uncommon to observe all the courses of a retaining wall

in a dilapidated condition after it has been built a comparatively few years. When the snow melts in the spring the water sinks into the ground and issues through every crack and crevice in the wall. As it collects along these fissile planes it freezes and wedges apart the laminæ of the rocks.

Because the sedimentary rocks more frequently have parting planes than the igneous, they are as a class more apt to suffer from alternate freezing and thawing. On the other hand the sedimentary rocks are sometimes as free from parting planes as the igneous, and are accordingly in as little, or even less, danger from freezing.

The openings known as caves, caverns, and cavities need not occupy our serious attention. Cavities occasionally occur in both sedimentary and igneous rocks used as building stone, but mainly in the former. They do not increase the danger from freezing, owing to the fact that they are seldom filled with water when near the surface. They weaken the rock slightly and often occasion a roughness of the face when they occur at the surface. The cavities are often partly filled with impurities, such as pyrite, which may injure the rock, through the readiness with which they decompose.

From the foregoing we may conclude that an ordinarily well cemented sandstone, which is free from parting planes or stratification, and in which the pores are of greater than subcapillary size, is best suited to withstand alternate freezing and thawing when placed in the wall of a building; assuming that the original strength of the stone is sufficient for the position which it occupies in the wall.

Mechanical abrasion.— One of the most important agents of disintegration in nature is mechanical abrasion, but the rôle which it plays in the destruction of artificial structures is not nearly as important as that of certain other agents.

Mechanical abrasion is accomplished mainly by wind, running water, and shuffling feet working in conjunction with the other agents of disintegration. The beating of the rain against the stone wall may overcome the adhesion between the rock

particles, separate them from one another, and carry them away. These particles may, in turn, as they are carried down the side of the building, wear off other particles, and so on until the bottom is reached. The effects of drifting sand, that are such conspicuous features of the arid regions, are very slight in the temperate zone in which we live. Drifting sand contributes an almost insignificant part to the whole process of disintegration. J. C. Smock, in his report on the building stone of New York, mentions the fact that the ground glass character of many of the window panes in some of the older houses of Nantucket are due to driven sand. The windward sides of many of the monuments in the older eastern cemeteries have lost their polish, while in some cases even the lettering has been destroyed by this same agent. The monuments in the cemeteries of Wisconsin which are located in sandy regions are beginning to show the effects of wind-blown sand. The polish is dulled and the lettering is becoming indistinct.

Besides being subject to the action of wind-blown sand and rain, stone is often used in places where it is abraded by thousands of feet passing over its surface. There is a great difference in the capacity which different stones possess to withstand abrasion. Sidewalks, pavements, and steps may be seen in every city which are more or less worn by constant shuffling of feet over their surfaces.

Growing organisms.— It is a very common occurrence to find lichens and algæ covering the surface of a rock in a quarry. Trees may also be observed sending their roots deep into the crevices and cracks of the rock, and by their growth and expansion huge blocks are often broken from the parent mass. In some of the very soft rocks the writer has observed the finer rootlets ramifying through the body of the rock itself, destroying the adhesion which bound the particles together. Decaying plants are also known to give off organic acids which aid in the decomposition of the rock. Fungi and algæ often attach themselves to the stone, frequently almost entirely covering the exposed surface. The most common form of plant growth

occurring thus is the lichen, which often covers the surface of the rock after the manner of a mat, thereby exerting a protective as well as a destructive influence. The covering which they form serves as a protection against the atmosphere, while the acids incident upon their decay and the mechanical effects of their rootlets penetrating between the grains are a slow cause of disintegration. Algæ are also common, and often occur on the damp parts of a wall, causing discoloration through their own decay and the lodgment of fine dust particles. The effect of allowing creeping vines, such as ivy, to cover the walls of buildings is picturesque, but the practice is certainly injurious to the life of the stone.

Careless methods of working and handling.—The natural forces of destruction have been greatly accelerated, either through the ignorance of quarrymen and their total disregard for proper time and methods of quarrying, or through the carelessness of workmen in cutting, carving, and laying the stone used in building construction. There are probably thousands of buildings, constructed out of stones, the lives of which have been shortened at least one half by improper methods of quarrying and handling.

Quarrymen have been found moving stone with heavy charges of powder, or even dynamite, expecting to obtain dimension stone for building purposes. The heavy charges of powder not only destroy a large amount of stone, but they also shatter the cement and produce incipient joints in the blocks which may accidentally remain in dimensions sufficiently large for building purposes. The destruction of the cement and the production of incipient joints not only weaken the rock, but also facilitate the entrance of water, with the attendant dangers from freezing, with which we are already familiar. This method of quarrying not only materially lessens the value of the salable stone, but hundreds of tons of otherwise marketable stone is absolutely destroyed. The use of heavy hammers and sledges in splitting the stone, by striking continuously along one line, shortens the life of the stone in the same manner as heavy blasting.

Much care should be exercised in quarrying stone in order to prevent these unnecessary injuries. So far as practicable, quarrymen should take advantage of the natural joints. Whenever blasting becomes necessary, the Knox system of small charges, properly distributed, is reported to be the least injurious of any method yet employed. The channeling machine, however, is the best method of reducing the stone to dimensions that can be easily handled. Especially in working sandstone and limestone this machine can be employed to advantage.

The time of cutting and dressing stone may also influence in a small way its life It is generally known that during the process of seasoning the water which comes from within the rock evaporates and deposits mineral matter which forms a crust on the surface of the stone. This crust may be formed entirely by the evaporation of the original interstitial water, or it may be added to by water which has been soaked into the stone at a later period and been subsequently brought to the surface.[1] That water, which has been called the water of imbibition, probably carries a much larger percentage of mineral matter in solution than the water of saturation. The water of imbibition is the last of the quarry water to leave the stone, and therefore the crust is not likely to be well formed until the rock has been thoroughly seasoned. If the stone is to be seasoned before being placed in the wall, it is advantageous to have it first cut, dressed, and carved. Not only is it advantageous to observe this rule from the standpoint of future durability, but also from the fact that the stone often works much more readily when first quarried than it does after it has been seasoned. After a crust has once formed it should not be broken, because the softer rock underneath, when exposed at the surface, will disintegrate much more rapidly. For these reasons most stone should be worked and finished, ready for laying in the wall, before it has been thoroughly seasoned.

[1] The addition through saturation and evaporation after the quarry water has been driven off is probably an almost unappreciable amount, depending upon the amount of mineral matter originally in the water.

The manner of dressing a stone also influences in a small way the length of its life. A stone which has polished surfaces sheds water much more quickly and is disintegrated much more slowly than one with rough surfaces. The stone with rough surfaces has many crannies and crevices, in which the water collects and is finally absorbed. Sandstone which has been hammer-dressed is liable at first to disintegrate faster than that which has been sawed, due to a weakening of the cement by the impact of the hammer. In general, it may be said that polished and sawn surfaces shed water most readily, while those that are rock-faced or hammer-dressed, on account of their rough exterior, absorb a considerably larger percentage of the water which falls on their surfaces.

Before a stone is used in the construction of a building it is safer to have at least the water of saturation driven off. As a rule quarrymen are acquainted with the effects of frost upon stone in which the water of saturation still remains, and observe the necessary precautions. There are quarrymen, however, interested solely in the disposition of their stock, who impose upon the ignorance of the public by selling stone which has not been seasoned. Stone should be seasoned not only to escape the danger from freezing, but also to insure safety in handling and laying.

The exfoliation of sandstone in the large eastern cities has been mainly attributed to the fact that much of the stone has been laid on edge instead of on the bed. Laying stone on edge has been practiced at all times, owing to the greater readiness with which stratified or schistose rocks can be dressed along the bed. The greatest tendency to lay stone on edge is encountered in veneer work, but is occasionally met with in heavy masonry.

If the parting planes, which ordinarily furnish the easiest paths for percolating waters, are normal or inclined to the surface of the earth, they will admit the passage of water much more readily than if they are parallel. Thus if a block of stone is placed on edge in a wall, there will be greater danger from the

freezing of the included water than if it were laid on the bed. In case the stone is laid on edge, the pressure required to split off lamina will ordinarily be much less than if the stone is laid on the bed. In the first case the force occasioned by the freezing of the water which collects between the layers is augmented by the superincumbent pressure of the wall. If the stone is laid on the bed, the water is less apt to penetrate along the parting planes, and even though it should circulate with equal freedom in this position, the superincumbent pressure of the wall would tend to force the expansion in directions parallel to the bedding.

Furthermore, when stone is laid on edge the difference in texture of the various laminae are much more strikingly emphasized than where the stone is laid on the bed. When laid on edge the different blocks, as a whole, will exhibit different rates of wear, instead of the minor inequalities ordinarily shown by the different laminae when the block is laid on the bed.

In important structures one ought to avoid laying any stone on edge which shows stratification or schistosity for the reason that in this position it is inherently weaker and permits a more ready absorption of water, with the attendant dangers from alternate freezing and thawing.

AGENTS OF CHEMICAL DECOMPOSITION

In artificial stone constructions the decomposition of the mineral constituents of a rock proceeds much more slowly than disintegration. The forces which are at work breaking down the chemical compounds have a much greater task to perform than those which have simply to overcome adhesion and cohesion.

Water.—The active agent producing chemical changes in the rock is water. Water generally contains in solution, besides mineral salts, one or more acids, either sulphuric, sulphurous, carbonic, or organic. Thus the water is often a very dilute acid solution. As it percolates through the rocks it dissolves small quantities of mineral matter in one place and deposits it in another. Through these agents the minerals composing the rocks of both the igneous and sedimentary series are decomposed, and transfers of large quantities of mineral substances take place.

In the case of building stone the chemical decomposition of the minerals is so exceedingly slow that it seldom affects the strength or life of the stone after it has been placed in a building. Only in the case of limestone, dolomite, or marble, or where iron sulphide or iron carbonate occur in other rocks, is any material deterioration noticeable.

Sulphurous acids.— In the case of decomposition of iron sulphide, in the presence of moisture, the formation of iron oxide is the most conspicuous, although not the only result. The decomposition of the sulphide produces sulphurous and sulphuric acids which, in the case of dolomite, act upon the magnesium carbonate, producing magnesium sulphate, which is often brought to the surface and deposited as an efflorescence or incrustation.

The sulphurous and sulphuric acid gases are mainly present in the atmosphere of large cities where there is a large consumption of bituminous coal. The action of these acids is largely increased if the atmosphere contains a considerable amount of moisture. In London, where fogs predominate and the consumption of soft coal is very large, there seems to be little question but that the effect of these gases is worthy of careful consideration. But in the United States, with the exception of a few of the larger cities, the influence of these agents is comparatively small and needs but a passing mention.

Carbon dioxide.—Wherever water heavily charged with carbonic acid gas is passed through calciferous rocks, more or less of the calcium carbonate is dissolved, lessening the adhesion between the different particles and weakening the rock. In nature the results of this process are very great, but the carbon dioxide has scarcely any appreciable affect on the durability of stone in the walls of a building.

Organic acids.—The influence of organic acids resulting from decaying organisms on the life and strength of a rock, especially in the walls of buildings, is so slight as to barely warrant mention.

E. R. BUCKLEY.